

Halon Replacement Program (HRP) for U.S. Army Ground Combat Vehicles

REPORT TO HALON OPTIONS TECHNICAL WORKING GROUP CONFERENCE

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ABSTRACTS

For HOTWC 2006 the following three oral presentation abstracts are combined into a single paper to provide a cohesive description of the entire program without repeating information.

Title: Hand-held Fire Extinguisher (HFE) Halon Replacement Program (HRP) for Army Ground Vehicles, Status and Successes.

The research program to identify alternatives to Halon 1301 used in fire extinguishing systems of Army ground vehicles is complete. Three programs of record are in various stages of completeness, crew compartment, hand held and engine compartment. This paper focuses on the hand-held (portable) fire extinguisher (HFE) replacement program and its status.

Several different portable design solutions were identified that could satisfy the requirements of the HFE replacement program. Several of the designs tested, claimed by their vendors to be a "drop-in" replacement for the Halon 1301 HFE, however, no systems tested as a direct size, weight and effectiveness replacement for the existing vehicle mounted portable bottles.

Two candidates, carbon dioxide (CO₂) and water with additives (H₂O+), emerged as replacements for the existing HFE.

The HFE replacement is complete for most Army vehicles. This presentation will review the research and update the attendees on the progress of the installations.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 10 MAY 2006		2. REPORT TYPE N/A		3. DATES COVERED -	
4. TITLE AND SUBTITLE Halon Replacement Program (HRP) for U.S. Army Ground Combat Vehicles				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) McCormick, Steve; Clauson, Mike				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) USA TACOM 6501 E. 11 Mile Road Warren, MI 48397-5000				8. PERFORMING ORGANIZATION REPORT NUMBER 15837 RC	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S) TACOM TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release, distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 17	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

Title: Engine Compartment Halon 1301 Replacement Program (ECHRP): Status And Successes.

The research program to identify alternatives to HALON 1301 in fire extinguishing systems (FES) of Army ground based systems, tanks and trucks is complete. Three programs of record are in various stages of completeness, crew compartment, hand held and engine compartment. This paper focuses on the engine compartment halon replacement program (ECHRP) and its status.

Several different FES design solutions were identified that could satisfy the requirements of the ECHRP. None of the FES tested were a “drop-in” agent or distribution replacement system. Testing dramatically demonstrated that the ability of any FES to extinguish combustion is as dependant on the agent distribution system for optimum effectiveness as it is on the agent itself.

We transmitted the test results, analysis and recommendations, to the vehicle Program Executive Officers (PEOs) and Program Managers (PMs). Based on the needed optimizations of their individual pieces of equipment, they would choose one of two concepts recommended for fire extinguishing within vehicles. These were a ‘heptafluorocarbon’ (FE-36, FM-200, isomers of, etc.) and a dry powder based extinguishant system. The Bradley PM is has adopted an FM-200 solution for their engine compartments and the Abrams PM is working a dry powder solution.

Engine compartment fire extinguishing system replacement is in process for many Army vehicles. The proposed presentation will update the attendee on the progress of the installation and the expected long-term effects to total Army logistics.

Title: Crew Compartment Halon Replacement Program for Automatic Fire Extinguishing Systems (AFES): Status And Successes.

The research program to identify alternatives to HALON 1301 in automatic fire extinguishing systems (AFES) of Army ground vehicles is complete. Three programs of record are in various stages of completeness, crew compartment, hand held and engine compartment. This paper focuses on the crew compartment replacement program for AFES and its status.

Several different AFES design solutions were identified that could satisfy the requirements of the crew replacement program. None of the agents tested are considered a “drop-in” for the agent into existing vehicle distribution systems. Testing dramatically demonstrated that the ability of any AFES to extinguish combustion is as dependant on the agent itself as it is on the agent distribution system for optimum efficacy.

The test results, analysis and recommendations transmitted to vehicle Program Executive Officers (PEOs) and Program Managers (PMs) guided their decision process. Based on the needed optimizations of individual pieces of equipment, the PEO/PM would choose one of two concepts recommended for fire extinguishing within vehicle crew compartments. These two concepts were an HFC (FM-200 or equivalent) with 5% dry powder and a water based extinguishing system to replace the crew AFES.

The crew compartment AFES replacement is in process for Army vehicles. This presentation will review the research and update the attendees on the progress of the installation.

INTRODUCTION

Halon 1301 has been used for decades as the primary fire and explosion extinguishing material for a multitude of industrial and military applications. However, halons have very high ozone depleting potentials and their production was stopped in 1994 in most of the world. The U.S. Army Tank-Automotive Research, Development and Engineering Center (TARDEC), the laboratory of the U.S. Army Tank-automotive and Armament Command (TACOM) that conducts research on issues affecting ground combat vehicles, initiated the Halon Replacement Program (HRP) to identify and develop replacement technologies to satisfy the performance and logistics requirements of fire protection for ground combat vehicles.

Early investigations indicated that a universal solution would not be available to the fire protection community for all the systems that used halon. Hence, multiple agents would probably be required to address the wide range of military applications currently satisfied by halon 1301.

This paper summarizes the results and findings of the HRP. It addresses the halon elimination efforts in three separate ground combat vehicle applications: engine compartment fire suppression, crew compartment explosion suppression, and hand-held fire extinguishers.

ENGINE COMPARTMENT

TEST SET-UP

The engine compartment program halon replacement program was divided into three phases. Phase I testing was conducted in an M60 tank hull using a non-functional power pack with combustible materials not required for conduct of the test removed. Airflow was rerouted to draw air in through the exhaust grille, past the engine and out through the turret using an external exhaust blower. This phase of testing was originally structured with six fire scenarios:

Type I	Combined Bilge Fire and Fuel Spray with Airflow
Type II	Combined Bilge Fire and Fuel Spray w/o Airflow
Type III	Bilge Fire with Airflow
Type IV	Bilge Fire w/o Airflow
Type V	Fuel Spray with Airflow
Type VI	Fuel Spray w/o Airflow



Figure 1. Phase I Test Setup

The Type I fire scenario (shown above) was conducted as follows: A combined Class A/B fire consisting of eight gallons of JP-8 fuel was ignited and allowed to burn for 1.5 minutes. The exhaust blower was then operated at 11,000 cfm (approximately two air exchanges per second) for another 1.5 minutes. A fuel spray consisting of heated JP-8 pressurized to 40 psig was then discharged through an 1/8" orifice onto a 1200°F heated surface. The spray continued for 15 seconds before the agent was manually discharged. The fuel spray continued for 30 seconds after extinguisher activation. Fire severities were scaled so that seven pounds of halon would be required to reliably extinguish the fires. The test parameters of airflow, fuel spray, and/or bilge ignition were varied to create the other fire types.

Minimum agent weights required to extinguish the fire without reflash were determined. No fire-out time criterion was used. As testing progressed it was determined that the Type I fire was too severe - none of the agents, including Halon 1301, could extinguish it without reflash, and the Type IV scenario was too benign - almost all of the agents could extinguish it with minimal weight. With sufficient preburn times, Type V and VI fires became Type I and II fires, respectively. Therefore, testing focussed on the Type II and III fire scenarios. The Type III fire represents a typical fire that an automatic system (e.g., M1 Abrams first shot) would be expected to encounter, while the Type II fire represents a severe fire that a manual system (e.g., M1 Abrams second shot or M2/M3 Bradley) could encounter.

PHASE I RESULTS

The results of Phase I testing are summarized below:

Table I. Phase I Agent Weights and Volume

<u>Agent</u>	<u>Weight (lbs)</u>		<u>Volume (in³)*</u>
	<u>Type II</u>	<u>Type III</u>	
Halon 1301	5.0	7.0	204
CO ₂	8.0	12.0	576
FM-200	9.0	7.0	288
FE-36	9.0	9.0	288
FE-25	< 9.5	9.0	~387
PGA	8.5	Unknown	??
Dessikarb	2.0	6.6	204
HGG/FM-200	12.4	9.3	320
Water mist	17.0	8.7	610
*storage volume of agent with overpressure required to extinguish both Type II and III fires			

CO₂: CO₂ was tested in the standard M60 delivery system. CO₂ was tested as a baseline for Phase I, but due to its large agent storage volume requirements, it was not pursued in Phase II.

FM-200: FM-200 (HFC-227ea) was tested with several different distribution systems, but the best performance was achieved with the standard M60 CO₂ distribution system. It performed better against Type III fires than it did against Type II fires due to its higher boiling point. The long preburn times and high surface temperatures may enhance its performance relative to Halon. FM-200 appears to extinguish fires much slower than Halon 1301 (4-12 seconds vs. 1 second) because of its slower vaporization. FM-200 was also successful at low temperatures (-25°F and below). There is approximately a 40% volume penalty relative to Halon 1301. Fill density is a critical factor when considering bottle size for FM-200. A minimum of 30% ullage is required to ensure sufficient N₂ for complete agent discharge from the extinguisher. FM-200 was tested in Phase II.

FE-36: The performance characteristics of FE-36 (HFC-236fa) are very similar to FM-200. Given the advantages of having two agents that perform equivalently in common hardware, FE-36 was tested in Phase II.

FE-25: FE-25 (HFC-125) was tested with the standard M60 CO₂ distribution system. Due to its lower liquid density at high temperatures, FE-25 is approximately 25% less efficient by volume than FM-200 or FE-36. Therefore, FE-25 was not tested in Phase II.

PGA (Envirogel): Several formulations of Powsus Gelled Agent (PGA, a.k.a. Envirogel) were tested in Phase I. The formulation favored by the manufacturer was FE-25 mixed with finely ground ammonium polyphosphate (APP) and a gelling agent overpressurized with nitrogen. The agent was tested in standard halon extinguishers with modified distribution tubing.

Single stage solenoid valves needed to be cleaned after each discharge and rebuilt after every two to three discharges and pilot valves after every discharge. Consistent results were not obtained with PGA against Type III fires, possibly due to insufficient gelling of the mixture. PGA was not tested in Phase II.

FluoroIodoCarbons: In earlier tests trifluoromethyliodide (CF_3I) had been shown to be at least as effective as Halon 1301 using existing distribution hardware. However, emerging toxicological findings eliminated CF_3I from consideration. Heptafluorobutyliodide ($\text{C}_3\text{F}_7\text{I}$) was substituted in Phase I with encouraging results, but it also had severe toxicological penalties and was not evaluated further. The fluoroiodocarbons were not tested in Phase II.

Dessikarb: Dessikarb (DXP) is a finely ground sodium bicarbonate based dry powder. It was tested with squib valves and distribution tubing with multiple nozzles. DXP is more effective against Type II fires than against Type III. After several distribution changes, the DXP proved to be as effective as Halon 1301 by volume. DXP was chosen in part because it is much less corrosive and cleanup is minimized. DXP and several other dry powders were tested in Phase II.

Gas Generators: Gas generators (GG) burn a solid propellant to rapidly produce large volumes of inert gases (N_2 , CO_2 , and water vapor). This technique is similar to that used in automotive airbags. New storage cylinders and distribution hardware are required. The GGs performed with mixed results against Type II and III fires. Additional development would be required to package this into a production configuration. The GGs were not tested in Phase II.

Hybrid Gas Generators: Hybrid gas generators (HGG) use the GG to pressurize and discharge a liquid agent, in this case water or FM-200. Both were more effective than the straight GG, but the water's freeze point problems were not overcome. The HGG with FM-200 extinguished fires much more rapidly than FM-200 overpressurized with nitrogen because the hot gases help vaporize the FM-200 and the extra pressure provided more consistent agent distribution. An HGG/FM-200 system was tested in Phase II. New storage cylinders and distribution hardware are required. Additional development of this technology is ongoing.

Water Mist: The water mist system uses relatively large volumes of water at high pressure (3000 psi). New storage cylinders and distribution system are required. While the system was quite effective against Phase I fire scenarios, freeze point and space claim issues were not adequately addressed. The water mist system was not tested in Phase II.

Water Spray w/Additives: Several additives have been found that lower the freeze point of water to -60°F or below and enhance fire extinguishment. The water spray was tested with the M60 CO_2 distribution system with mixed results. Research continues to identify additives that enhance performance as well as provide adequate freeze point suppression. Water sprays were not tested in Phase II because their performance was not equivalent to FM-200.

Spectronix Solid Propellant Generated Aerosol (SPGA): Solid propellant is burned generating inert gases and fine dry particle (~ 1 micron) aerosol. New storage containers and distribution system are required. Due to the buoyancy of the hot effluent, none of the test fires could be extinguished. The Spectronix SPGA was not tested in Phase II.

Dynamite Nobel SPGA: The Dynamite Nobel SPGA is similar to the Spectronix units except they are packaged so the effluent is cooler and the discharge can be more readily directed. New storage containers and distribution system are required. Type II fires could be extinguished with six canisters, but fires reflash. Mixed results were obtained for Type III fire tests. Available space in the engine compartment limited the number of canisters and locations. The Dynamite Nobel SPGA was not tested in Phase II.

Table II. Agent Properties

Candidate Trade Name	Chemical Formula	Liquid Density @77°F (lb/ft ³)	Vapor Pressure @77°F (psi)	Boiling Point (°F)	Ozone Depletion Potential (ODP)	Global Warming Potential ^{a,b} (GWP)	Atmospheric Lifetime ^a (yrs)
FM-200	C ₃ F ₇ H	86.7	66.5	2.5	0	2900	36.5
FE-36	C ₃ F ₆ H ₂	85.5	39.9	33.2	0	6300	209
FE-13	CF ₃ H	41.8	665	-115.7	0	11700	264
FE-25	C ₂ F ₅ H	78.0	190	-55.3	0	2800	32.6
PFC 410	C ₄ F ₁₀	94.0	42	28.4	0	7000	2600
PFC 614	C ₆ F ₁₄	105.0	4.5	132.0	0	7400	3200
Carbon Dioxide	CO ₂	49.2	929.5	-109.1	0	1	variable
Halon 1301	CF ₃ Br	96.0	234.8	-72.0	12 - 16	5600	65

a – from Intergovernmental Panel on Climate Change (IPCC) 1995 Assessment Report

b – based on 100-year time horizon calculated using CO₂ as reference

PHASE II RESULTS

The Phase II test fixture was based on an M60 tank with a functional power pack. Type II fires were conducted similarly to those in Phase I but without the three-minute preburn time. Type III fires consisted of a 15-second preburn, then the engine was brought up to approximately 1500 rpm and the agent was immediately discharged (25-30 seconds after fire ignition). These tests were conducted to validate that the minimum agent volumes identified in Phase I were adequate to extinguish realistic vehicle fires with an operating engine, not to further minimize the amount of agent required.

Based on these results, two agents were recommended to the vehicle program managers for Phase III testing: FM-200 and sodium bicarbonate based dry powder.

FM-200 is compatible with current extinguishers in the Army inventory. For distribution systems like the M1, minor modifications may be all that is needed but single nozzle distribution systems will probably need to be expanded to provide adequate agent dispersion. FM-200 has zero ozone-depletion potential. FM-200 also shows potential as a substitute for portable fire extinguishers and crew compartment fire extinguishing systems. However, an agent increase of approximately 40% by volume is required to achieve equivalent performance to Halon 1301. Agent recovery and recycling are recommended.

With proper distribution, sodium bicarbonate powder has been shown to be as effective as Halon 1301 in high airflow conditions, and even more effective than 1301 in low airflow tests. Its environmental impact is negligible. The cost of the powder is less than 50 cents per pound, and can be supplied by many sources. However, a more elaborate distribution system is required for the powder to work properly. Valves, tubing, nozzles, and check valves all will likely need to be replaced. Powder is not appropriate for fixed or portable extinguishers to be used in occupied compartments or near sensitive electronics.

PHASE III RESULTS

Phase III testing was conducted in actual ground vehicles with the two recommended agents. Fire scenarios were defined by the respective vehicle program managers based on specific system requirements and vehicle fire histories.

Following an exhaustive test program for the M1, M2/M3, M992, MLRS and M9 ACE, both agents were chosen for certain applications. In general, HFC-227ea is being installed in vehicles that shut the engine off prior to agent discharge (including the M2/M3 Bradley Fighting Vehicle Series) because of its ease of retrofit while sodium bicarbonate powder will be used in vehicles with an automatic extinguishing system (including the M1) because of its superior performance. This offers the lowest overall life-cycle-cost solution for the Army. Retrofit of the HFC-227ea has been completed for the M2/M3 and MLRS and the powder systems are being applied to the M1 family of vehicles.

CREW COMPARTMENT

With the exception of the former Soviet Bloc countries, Halon 1301 has been the agent of choice to protect vehicle crewmen against burns from ballistically-initiated fuel or hydraulic fluid fires. The US Army currently has three fielded ground vehicles using Halon 1301 to protect their crew compartments: the M1 Abrams main battle tank, the M2/M3 Bradley Fighting Vehicle, and the M992 Field Artillery Ammunition Support Vehicle (FAASV). The crew compartments of these vehicles range in volume from 250 to 700 ft³ and employ from seven pounds of halon 1301 in a single shot to 21 pounds in each of two shots. We also must consider future ground combat vehicles with crew protection, including the Crusader, the Interim Armored Vehicle (IAV), the Future Combat System, and the US Marine Corps Advanced Amphibious Assault Vehicle (AAAV).

The Army Surgeon General has established the guidelines shown in Table III as the minimum acceptable requirements of automatic fire extinguishing systems for occupied vehicle compartments. These parameters have been established at levels that would not result in incapacitation of the crewmen from the fire and its extinguishment, allowing them to take corrective action and potentially to continue their mission.

Table III. Crew Survivability Criteria

PARAMETER	REQUIREMENT
Fire Suppression	Extinguish all flames without re-flash
Skin Burns	Less than second degree burns ($<2400^{\circ}\text{F}\cdot\text{sec}$ over 10 seconds or heat flux $< 3.9 \text{ cal/cm}^2$)
Overpressure	Less than 11.6 psi
Agent concentration	Not to exceed LOAEL*
Acid gasses	Less than 1,000 ppm peak
Oxygen levels	Not below 16 %
* LOAEL – Lowest Observed Adverse Effects Level	

The Army's crew compartment test program was divided into three phases. Phase I was a proof of concept and screening phase of multiple agents and technologies. Phase II consisted of further developmental testing of several of the most promising concepts from Phase I.

Based on performance and system integration issues, two agents were recommended to the vehicle program managers for Phase III testing, where prototype fire extinguishing systems are to be evaluated in the affected ground vehicles.

TEST SETUP

The crew test fixture was constructed from an excess ground vehicle hull and turret. A top down layout of the fixture is shown in Figure 2, below. The fixture had an interior volume of approximately 450 ft³ empty as used in Phase I testing. For Phase II, three "tin" mannequins and a four-unit TOW missile rack (added in dashed lines) were added to simulate partial vehicle stowage. The cargo and turret hatches and ramp door were secured during each test while the driver's hatch was allowed to pop open to relieve internal overpressures while minimizing airflow.

Instrumentation included high-speed and standard video, 1-micron infrared detectors, heat flux gages, thermocouples, and pressure gages. Four types of instrumentation measured acid gas exposure levels: ion selective electrodes (grab bag sampling), sorbent tubes (NIOSH procedure 7903), midjet impingers, and FT-IR analyzers. The FT-IR was the only one of these methods that reported levels of the gases themselves, as opposed to fluorine or bromine ions. Gas species tested for included oxygen (as O₂), hydrogen fluoride (HF), hydrogen bromide

(HBr), and carbonyl fluoride (COF₂). Nitrogen oxide (NO), nitrogen dioxide (NO₂), carbon oxide (CO), and carbon dioxide (CO₂) levels were also monitored during certain gas generator tests.

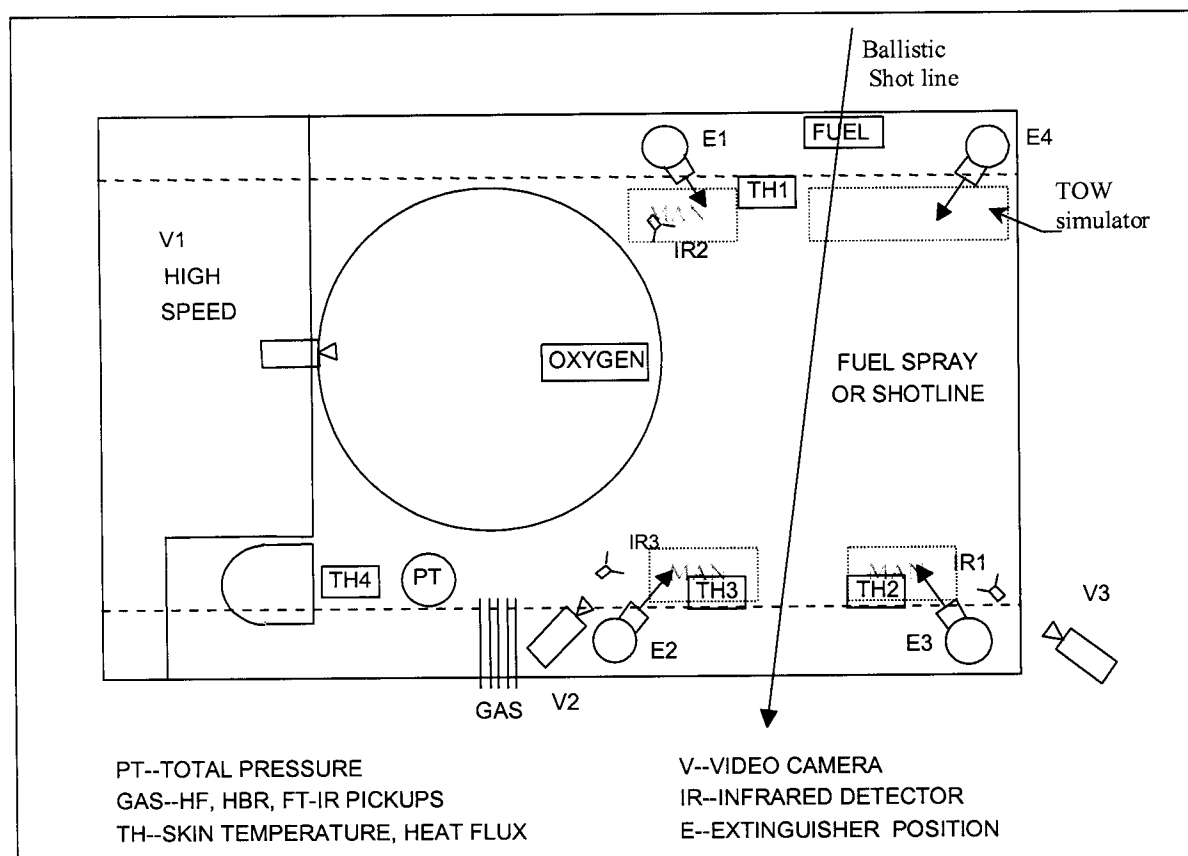


Figure 2. Crew Compartment Test Fixture.

Two test scenarios were conducted in Phases I and II: fuel spray fires and ballistic penetrations. The spray fire was generated with approximately 0.3 gallons of JP-8 heated to 180-190°F and pressurized to 1200 psi using a specially designed nozzle. Fuel flow continued for approximately 1.2 seconds with the igniter energized for the duration of the spray to simulate the re-ignition sources present during a typical ballistic event. The spray fires were monitored with three one-micron infrared detectors. The extinguishing system was activated automatically after an 11-millisecond delay from the time the fire energy reached a predetermined threshold. Ballistic fires were generated by firing a 2.7 inch shaped charge through an 18.7 gallon (2.25 ft³) capacity aluminum fuel cell filled with 11 gallons of JP-8 heated to 165°F. The fire extinguishing system was activated 25 milliseconds after warhead initiation to eliminate the variability of the detection system.

PHASE I RESULTS

A sample of baseline test results is found in Table IV. The data are consistent with two trends that we expect to find in this environment:

- 1) Delivery of the agent is as important, or more so, than the agent itself, and
- 2) The faster the fire is extinguished, the lower the by-product levels (acid gases) are.

Table IV. Phase I (w/o clutter) Baseline Ballistic Test Data

Agent ‡	Total Weight (lbs.)	Bottle Config # x in ³	IR fire-outs (msec)	Video fire-outs (msec)	2-Min Avg. HF (ppm)	Peak HF (ppm)
Halon 1301	8.1	2 x 144	241 – 555	~ 202	1500 – 2200	Unavailable
Halon 1301	10.0	3 x 144	161 – 384	120 – 368	300 – 1000	1300
Halon 1301 + BCS	10.0 + 0.3	3 x 144	440 – 3000	120 – 142	300 – 500	600
FM-200	11.9	2 x 144	Reflash	220 – unk	19500 – 20600	Unavailable
FM-200	12.1	3 x 144	~ 2200	250 – 980	1700 – 4500	Unavailable
FM-200	14.7	3 x 144	2000 – 4000+	reflash	2800 – 3000	12700
FM-200	15.0	4 x 144	211 – 234	200 – 320	900 – 1200	1400
FM-200 + BCS	12.2 + 0.3	3 x 144	189 – 358	100 – 170	BDL	BDL
‡ - All tests used the 'standard' Army extinguishers and nozzles with N ₂ overpressure. BCS - bicarbonate of soda powder added to liquid agent BDL - below detection limits (less than 35 ppm)						

Several alternative concepts were also evaluated under Phase I. They can be divided into five categories: fluorocarbons (i.e., HFCs and PFCs) with nitrogen overpressure, water spray with nitrogen overpressure, hybrid gas generators with HFCs, hybrid gas generators with water, and novel distribution systems (e.g. wet main systems). Typical distribution systems are illustrated in Figure 2.

Various additives to inhibit freezing and enhance effectiveness of the water and to neutralize acid byproducts generated from the HFCs were also investigated. Representative data are displayed in Table V for several of the configurations tested. Thermocouple and heat flux data indicate that burn thresholds are not being exceeded under these scenarios for either the ballistic or the spray fire for the HFC-227ea/dry powder systems.

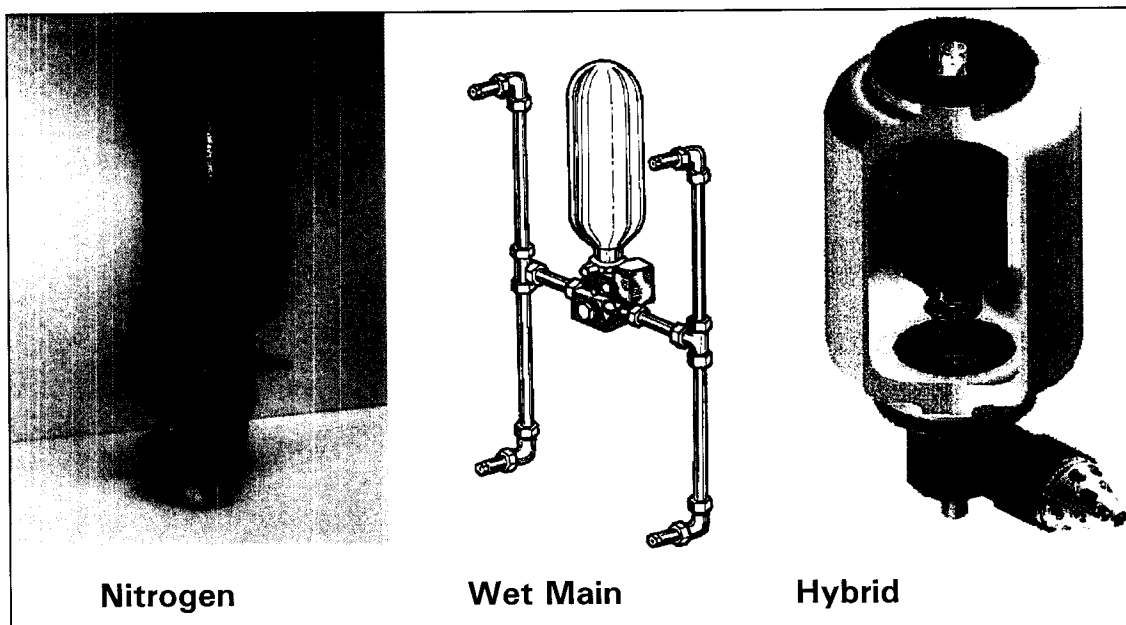


Figure 3. Candidate Agent Delivery Methods

Table V. Phase I (w/o clutter) Ballistic Test Data

Agent / Distribution system	Total Weight (lbs.)	Bottle Config. # x in ³	IR Fire-out (msec)	Video Fire-out (msec)	1-Min Avg. HF (ppm)
CEA-308 – ss	19.1	4 x 144	120 – 123	100 – 110	4600 – 4800
CEA-308 + BCS – ss	19.4 + 0.5	4 x 144	157 – 181	120 – 150	1150 – 1800
FM-200 – ss	18.0	3 x 204	213 – 302	106 – 200	2600 – 2900 ¥
FM-200 – gg	15.9	3 x 126	186 – 239	106 – 150	1400 – 6800 ¥
FM-200 + BCS – ss	16.4 + 1.5	3 x 204	180 – 227	162 – 170	100 – 600
FM-200 + BCS – gg	10.0 + 1.25	3 x 84	134 – 149	104 – 150	100 – 400
H2O/Kace – gg	33.6	2 x 244	184 – 253	118 – 250	n/a
H2O/Kace – gg	21.0	3 x 147	160 – 383	92 – 168	n/a
H2O/KAce – wm	10.5	3 x 204	124 – 215	90 – 300	n/a
¥ – two minute average ss – standard Army system with nitrogen overpressure gg – gas generator for agent expulsion wm – wet main distribution system					

PHASE II RESULTS

The baseline tests of Phase I using standard Army extinguishers were repeated with clutter and the results are shown in Table VI. As can be seen by comparing tables II and IV, the clutter increased the fire suppression challenge. Based on the results of Phase I and guidance from the EPA Significant New Alternatives Policy (SNAP) program, wet mains and hybrid gas generators, and combinations thereof, and HFC-227ea/dry powder and water/potassium acetate agents were selected for further evaluation in Phase II.

Table VI. Phase II (w/clutter) Baseline Test Data

Agent ‡	Total Wt (lbs)	Bottle # x in ³	IR Fire- (msec)	Video Fire-Out (msec)	2-Min Avg. HF (ppm)	Peak HF (ppm)
1301	9.9	3x144	777-1023	750-1000	2100	10300
1301	16	4x144	159-167	150-180	1800	3500
1301	12	4x144	179-193	180-220	1500	2000
1301	10	4x144	189-268	220-250	1100	1300
FM-200	16	4x144 §	172-216	180-240	800	1100
FM-200	12	4x144	185-220	190-260	1300	1600
FM-200+BCS ¶	12+1	4x144	173-214	180-220	70	150
‡ - All tests used the 'standard' Army equipment bottles, valves and nozzles. § - bottles reoriented for this and subsequent tests ¶ - 0.25 pound of sodium bicarbonate was added to each extinguisher.						

Representative results of the Phase II ballistic tests with clutter are shown in Table VII. Note that the improved distribution systems accounted for reduced extinguishing times and lower HF levels even while using less agent and/or fewer extinguishers. Even for those tests with extended extinguishing times the byproduct levels were significantly lower than for equivalent tests in Phase I or baseline tests of Phase II.

Table VII. Phase II (w/clutter) Ballistic Test Data

Agent /Delivery System	Total Wt (lbs)	Bottle # x in ³	IR Fire- (msec)	Video Fire-Out (msec)	2-Min Avg. HF (ppm)	Peak HF (ppm)
FM-200 - gg	18.0	3x195	93-96	92-140	320	330
FM-200 - gg	18.0	3x195	106-135	86-210	230	950
FM-200 + BCS - gg	18.0+0.6	2x192	159-188	152-180	50	70
FM-200 + BCS - gg	15.0+0.6	2x195	34-385	450	330	380
FM-200 + BCS - gg	12.0+0.6	2x142	277-431	400-730	560	790
FM-200 - wm	16.2	Wet main	407-937	784-1000	1500	2100
FM-200+BCS - wm	11.2+0.8	Wet main	1272-1656	810-1290	700	1300
H ₂ O/Kace - gg	10.2	3x142	136-156	124-200	n/a	n/a
H ₂ O/Kace - gg	10.2	3x142	180-245	102-350	n/a	n/a
H ₂ O/Kace - wm	24.0 *	Wet main	221-317	260-650	n/a	n/a
gg – gas generator for agent expulsion wm – wet main distribution system * - discharge extended well beyond extinguishing time						

PHASE II OBSERVATIONS

Baseline tests with Halon 1301 and HFC-227ea using standard Army extinguishers and nozzles indicate that a total agent weight of ten pounds of 1301 delivered by three extinguishers is required to successfully extinguish both the fuel spray and ballistic fires. Lower agent weights lead to longer fire-out times and the byproduct levels rise significantly. Fifteen pounds of HFC-227ea provided approximately equivalent performance except the HF levels were elevated. However, HFC-227ea with a small amount of sodium bicarbonate imbedded or ‘suspended’ within the HFC required only 12 pounds of material (divided between four standard 144 in³ extinguishers) and dramatically reduced the HF in both the spray and ballistic tests. Temperature and heat flux data indicate that burn thresholds were not exceeded for either the ballistic or the spray fires for the HFC-227ea/dry powder systems tested.

The baseline data for Phase II is slightly different than that of Phase I (see Table VI). The data demonstrate the increased difficulty of extinguishing deflagrations while distributing the agent around clutter. It also points out the delivery system is critical in the overall optimization process for a particular fire/explosion scenario. Please note that the first line of data represents a poorly distributed system. There were only three 144 in³ bottles versus the better distribution of a four bottle system (see the 4th line). The effect is dramatically demonstrated by the peak HF concentration value being reduced by an order of magnitude and the halving of the 2-minute average HF concentration.

The following trends were observed:

- After achieving a successful fire extinguishment concentration, adding additional HFC does not necessarily further reduce the fire-out time, but can lead to significant reductions in observed byproduct levels.
- Discharging an acid scavenger along with the HFC can significantly reduce the HF levels, sometimes to below detectable levels. As little as 5 % by weight added to the HFC or stored in the nozzle has shown dramatic reductions in overall HF production. Overall, the BCS reduced the byproducts by an average of 50% independent of the delivery system used.
- The hybrid gas generators provide faster and more consistent discharges than the nitrogen overpressure system. This can result in faster fire-out times and significantly lower byproduct levels.
- Plain water sprays can suppress the initial fire event, but the fire typically reflashes within one second using simple nitrogen overpressure for agent expulsion. Freeze point suppressants (such as potassium acetate) can be added to the water sprays.
- Water/salt solutions successfully inhibit reflash of the fire and substantially reduce fire out times. These solutions can be highly conductive in the liquid form (up to

seven times that of water), but they may not be a significant conductivity problem when misted.

- Water/anti-freeze solutions delivered using gas generator hybrids successfully inhibit reflash and operate faster than Halon 1301 systems, providing cooling and operation against class A and B fires. Visibility reduction due to water/anti-freeze fog production and clean-up issues need to be further addressed.

Performance equivalent to halon 1301 can be achieved with available agents and delivery system technologies. Crew survivability criteria have been satisfied against ballistic fires with HFC-227ea concentrations well below accepted exposure limits. Adding small amounts of sodium bicarbonate powder to the HFC reduces acid gas formation by half. Water mist with potassium acetate salt also proved to be very effective with no concern of hazardous byproducts and simple cleanup. Hybrid gas generators offer a smaller overall envelope for the same agent weight, pressure on demand, and a more consistent agent discharge. Wet mains allow the agent to be prepositioned for very rapid agent dispersion and offer the flexibility of nozzle locations.

Therefore, the following two agents were recommended to the ground vehicle program managers for crew compartment explosion suppression in December 1999:

- 1) HFC-227ea with 5% sodium bicarbonate powder by weight added to minimize HF
- 2) A 50/50 blend of water and potassium acetate by weight to suppress the freeze point to below -60°F and to enhance suppression capability.

Because these agents don't vaporize as readily as 1301, more sophisticated delivery systems than the standard extinguisher with nitrogen overpressure may be required in certain vehicle applications. Other trade-offs must also be considered before final agent and distribution hardware decisions can be made. These include system integration and retrofit impacts, initial purchase and sustainment costs, maintenance burden, long-term environmental impacts and policies, and the viability of the Army's halon reserve.

PHASE III

Priority and focus of the crew halon replacement program have been on vehicles under development. The Stryker vehicle is the first combat vehicle newly developed for the Army since the phase-out of halon production. Based on the results of phase II, FM-200/powder agent was chosen for use in the Stryker crew compartment. This system and agent have successfully completed live-fire testing and now set the standard for future vehicles such as the Future Combat System (FCS) and defines the retrofit impact for current legacy vehicles including M1 Abrams, M2/M3 Bradley and M992 FAASV. The cost of retrofit versus current logistics costs is driving the decision to have the legacy systems rely on the Halon reserve stockpiles. While commonality is a goal, along with environmental stewardship, it is more cost-effective to consume the existing Halon reserve (a sunk cost) and then retrofit the legacy systems if/when Halon 1301 is no longer available or approved for use.

HAND-HELD FIRE EXTINGUISHERS

The US Army has relied on the 2.75-pound halon 1301 handheld fire extinguisher for decades. With the advent of environmental concerns related to the halons, however, the Army reverted back to the previous agent of choice – carbon dioxide. To date, more than 18,000 halon handhelds have been replaced with 2.5-pound CO₂ units in vehicles where crewmen are trained to exit the vehicle before fighting the fire from the outside (see Figure 4).

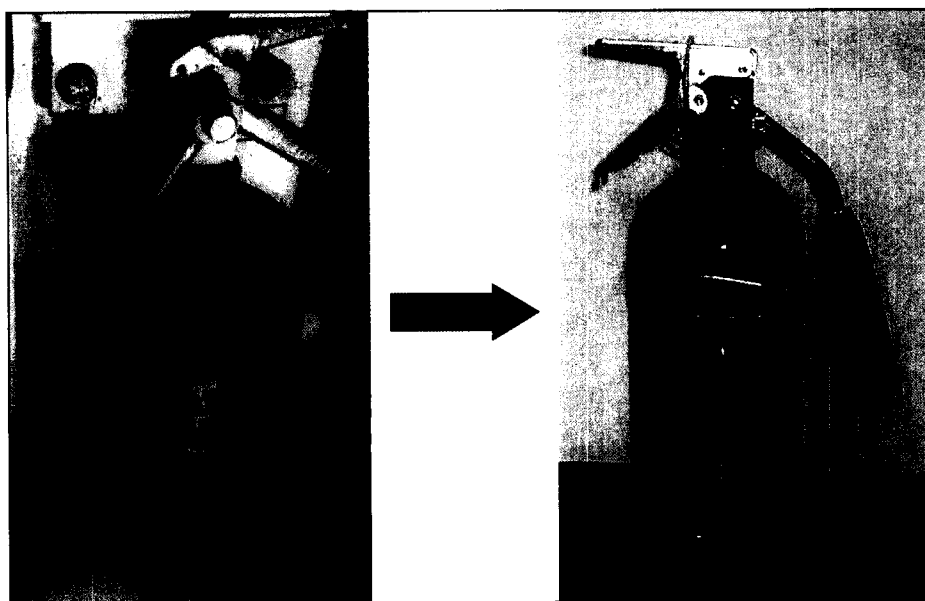


Figure 4. Halon 1301 and CO₂ Handheld Extinguishers

However, under some battlefield conditions the M1 Abrams tank crew may be required to stay under armor while fighting an internal fire. Under these circumstances, discharge of multiple CO₂ handhelds can result in potentially dangerous concentration levels. Therefore, due to these health concerns, the M1 retained the halon 1301 handhelds while research continued for an acceptable alternative.

A wide variety of alternatives have been evaluated for the M1, including HFCs, powder blends and water-based agents. FM-200 and FE-36 performed well at room temperature but exhibited poor low temperature performance and high byproduct levels. Certain halogenated alkanes were blended with the HFCs in attempts to improve performance but results were mixed. Two alternatives identified in the crew research underwent detailed evaluation: HFC-227ea with sodium bicarbonate powder added to improve performance and minimize HF and a 50/50 blend of water and potassium acetate by weight to suppress the freeze point to below -60°F and enhance suppression capability. The water/acetate hand-held was down-selected for this application due to its lack of pyrolysis products and its ability to combat Class A vehicle filter fires experienced by the Abrams. This hand-held will begin to be introduced to the field later this year.

APPLICATIONS

The following table gives examples of alternatives to halon 1301 that have been applied to Army ground vehicles:

Application	Extinguisher type	Use example
Hand Held Extinguishers	CO ₂	Bradley
	H ₂ O + acetate	Abrams
Engine Compartment	FM-200	Bradley FV
	FE-25	Stryker
	Dry Powder	Abrams
Crew Compartment	FM-200 + powder	Stryker

SUMMARY

The US Army has aggressively pursued alternatives to halon 1301 in its ground combat vehicles. Alternatives for all three ground vehicle applications have been identified and fielded. As of now, only the crew compartment explosion suppression system of our legacy vehicles, Abrams, Bradley and FAASV, are still reliant on halon.